

GNSS Activities and Performance at USNO

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Abstract—This paper presents selected recent GNSS activities in the Time Service Department at the U. S. Naval Observatory in Washington, DC. Items investigated include relative receiver calibration; evaluation of the recent performance of GNSS receivers; zero-age corrections applied to operational PPS receiver data to compute a better one-day value for the USAF; a brief presentation of an algorithm to detect and correct discrete jumps in time-series data including the potential applications; applications of PPP for GPS time transfer as well as the ability to determine receiver instability through common-antenna, common-clock PPP solutions; GPS Time Transfer Trips; USNO's contributions to the IGS MGEX; and progress on GPS-to-GNSS Time Transfer (GGTO).

I. INTRODUCTION

The U. S. Naval Observatory (USNO) is a leading timing laboratory in the world, as well as the official PTTI Manager for all U. S. Department of Defense (DoD) systems (per DoD Directive 4650.07 [1]). We make substantial contributions to UTC and provide timing support to many military and civilian programs. As such, investigation and research of precise timing and time transfer products and technology is paramount. In particular, GPS, and now more generically GNSS, has been used for decades to transfer time. Relatively recent developments in GNSS processing such as the Precise Point Positioning (PPP) algorithm have allowed GPS time transfer to approach the precision and accuracy of Two-Way Satellite Time Transfer (TWSTT). This paper presents some of the GNSS activities at Time Service Department at USNO as well as some recent performance of selected GNSS receivers.

II. DISCLAIMER

Several different GPS receivers are mentioned in this paper. USNO does not endorse any product or manufacturer.

III. RELATIVE RECEIVER CALIBRATION

GPS receivers that serve as primary timing receivers should be run continuously. However, it is still desirable to check and calibrate these receivers. A method for doing so is referred to as relative receiver calibration. To do this, one uses two or more receivers running on the same clock and antenna. Then, by differencing the raw datasets, a calibration for the operational receiver can be obtained. Furthermore, the user must take into account the signals to be calibrated. For a geodetic timing receiver, the signals of interest are the C1, P1, and P2 signals. When using a receiver which produces only C1 and P2 measurements, such as a NovAtel ProPak-V3, additional care must be taken when performing a relative calibration to a receiver producing C1, P1 and P2 signals, such as Septentrio or Ashtech receivers.

USNO recently switched its primary receiver to a NovAtel ProPak-V3 receiver, called USN6. Before doing so, the receiver was calibrated relative to the old primary receiver, USN3 – an Ashtech Z-XII3T. Figure 1 shows how the daily average P3 difference between USN3 and USN6 was affected by the calibration procedure. The beginning of the plot shows the initial offset between USN3 and USN6. The next couple of jumps occurs as the calibration procedure was established. The plateau which begins around MJD 56045 and persists for about 10 days is the result of calibrating the C1 of the NovAtel receiver

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to the C1 of the USN3 receiver. The 250 picosecond offset from zero is due to a hardware C1→P1 delay in the Ashtech receiver. The P1 signal is the signal of interest in the L1 frequency in dual-frequency precise timing applications, thus it is the P1 signal that is calibrated and not C1. To get P1 measurements from a receiver producing only C1, such as the NovAtel receiver used here, one must apply the C1→P1 biases. After observing this, the C1→P1 biases were applied to the USN6 RINEX observations using the program `cc2noncc`¹. These corrected observations were then differenced against USN3 P1 to form the final calibration seen beginning around MJD 56055. This calibration brings the receiver P3 difference essentially to zero within the error bounds of instability.

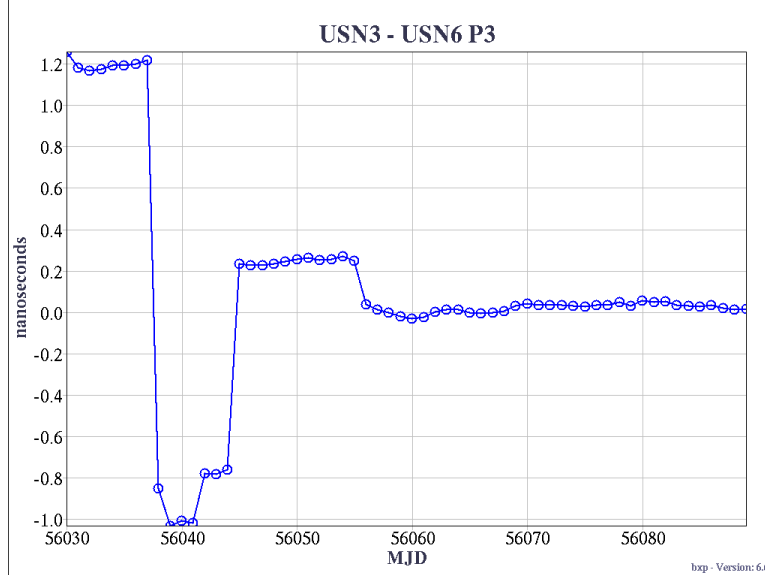


Figure 1. USN3 minus USN6 P3 Day Averages.

IV. USNO GNSS RECEIVERS

USNO employs a wide variety of GNSS receivers. On our primary Standard Positioning Service (SPS) antenna, there are four receivers of interest:

- USN3: This is a 20th century receiver, an Ashtech Z-XII3T. The room containing these receivers unfortunately has temperature fluctuations, and the receiver is subject to delay changes from this temperature instability. It also only tracks GPS. This was the USNO primary receiver up until September 2012.
- USN4: This receiver is also known internally as SPX3. It is a Septentrio PolaRx4TR Pro. It is designed to be able to track every GNSS in the sky. There is some interesting behavior in PPP reductions that will be shown later. USNO submits data from this receiver to the International GNSS Service (IGS) Multi-GNSS Experiment (MGEX).
- USN5: This receiver is also known internally as NOV2. It is a NovAtel FlexPak6 (based on the OEM628 board). It as well is designed to track everything in the sky, although currently it does not support COMPASS due to the lack of an official Interface Control Document (ICD). This is another MGEX receiver.
- USN6: This receiver is also known internally as NOV1. It is a NovAtel ProPak-V3 (based on the OEM-V3 board). It is GPS/GLONASS L1/L2 capable. The receiver family has been tested; it is

relatively stable over temperature shifts and has not exhibited any other timing anomalies. As of September 2012, this is the primary receiver for BIPM Circular-T and TAIPPP.

- NOVT: Another NovAtel ProPak-V3. This receiver is the traveling receiver used for GPS Time Transfer experiments.

Later in the paper, when PPP is discussed, there are some stability comparisons between these receivers.

USNO also has a traveling GPS receiver (another NovAtel ProPak-V3), and additional receivers for testing applications. For the Precise Positioning Service (PPS), USNO has several specialized receivers as well.

V. ZERO-AGE CORRECTIONS

USNO, in support of GPS as the official PTTI Manager for the U. S. Department of Defense, submits UTC corrections to the U. S. Air Force 2nd Space Operations Squadron (2SOPS). These corrections are currently based on an average of 1 day's data. 2SOPS uses these submissions in its operational Kalman Filter for the steering of GPS time and for the broadcast of UTC correction parameters in Subframe 4 Page 18 of the GPS Navigation Message.

2SOPS makes zero-age corrections available to authorized users in near-real-time. These corrections are Kalman filter outputs of position errors of the broadcast satellite position and clock from the calculated satellite position and clock from monitor station data. Similar to IGS ultra-rapid or real-time products, these corrections are especially useful when applied to older satellites with less predictable clocks long after they have been uploaded; this is due to the fact that older satellites have less stable clocks, and are thus less predictable as the time after upload increases. Using these corrections, the user is able to obtain more accurate a priori information regarding the GPS satellites.

USNO began using these corrections for testing purposes in the summer of 2010. We found that their use results in far fewer outliers in the data and much reduced noise. See Figure 2 for a plot of broadcast and zero-age corrected data. There is slightly improved performance in the 1-day averages (see Figure 3). The greatest benefit at one-day is the reduction of the noise of the dataset used in the average – as noted in Figure 2. In Figure 4, the Time Deviation shows that the greatest benefit relative to the broadcast-only solution is at sub-day averaging times. At extremely small averaging times, with $\tau \ll 1$ day, the data are dominated by noise (i.e. multipath) and additional techniques are needed to see continued benefits – such as carrier smoothing. Due to the nature of the GPS Time steering algorithm, there is a hump in the Time Deviation at about 1 week.

On November 1st, 2010, USNO began submitting the daily datasets using the zero-age corrections. The use of this zero-age product allows USNO in turn to deliver back to 2SOPS a better product that more accurately and precisely reflects the system offset of GPS to UTC (USNO).

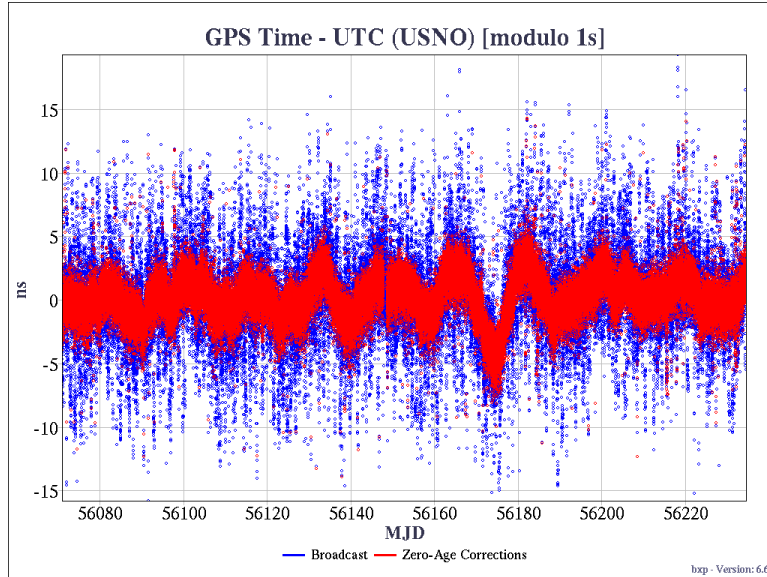


Figure 2. GPS Time minus UTC (USNO) [modulo 1s]. There are fewer outliers and less overall noise in the Zero-Age points, which overlay the broadcast points nicely. The RMS of the zero-age data is less than half of the broadcast data over any given day.

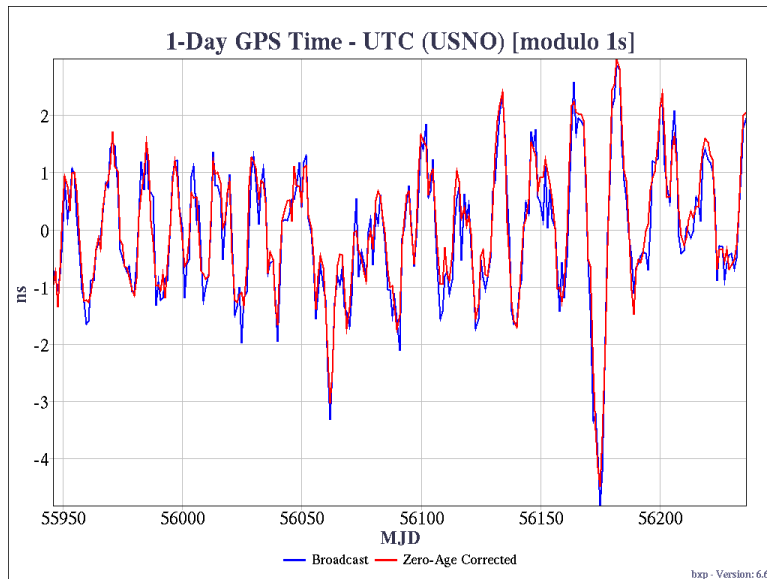


Figure 3. 1-day averages of GPS Time minus UTC (USNO) [modulo 1s]. Looking at a plot of 1-day averages, the benefit of using zero-age corrections is not immediately observable. The zero-age curve shows smaller excursions and rounds out some of the peaks and valleys.

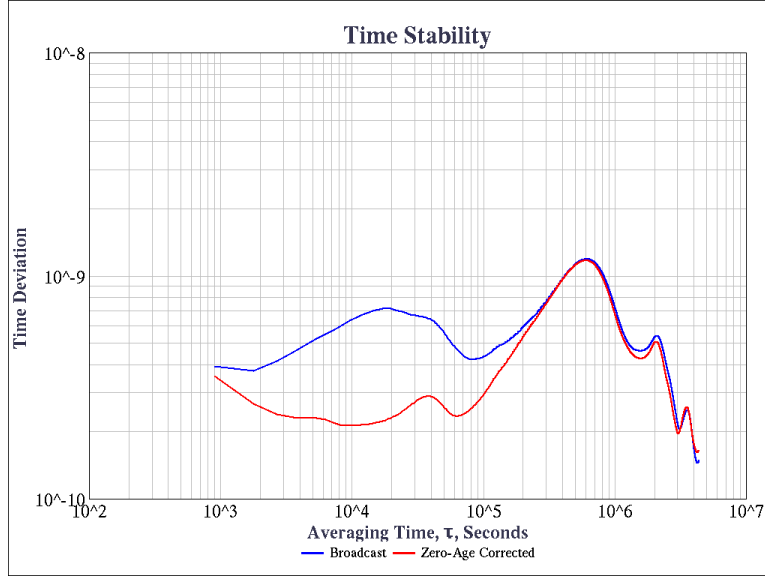


Figure 4. Time Stability of GPS Time minus UTC (USNO) [modulo 1s].

VI. DETECTING DISCRETE JUMPS IN TIME-SERIES DATA

Every attempt is made by USNO to keep GNSS receiver environments well-maintained. However, GNSS receivers can make unexpected, inexplicable wanders over time or suffer discrete timing jumps. It is important to be able to detect these jumps, especially in the event that a primary timing receiver is involved.

A method for precisely determining jumps after the fact is to difference receiver data. At USNO, we have several receivers, including our primary operational receivers, on the same antenna and clock. This facilitates direct differencing of raw receiver data.

Using differenced receiver data, it is possible to detect receiver jumps easily by eye. However, there are many sets of receiver differenced data to consider. It would be optimal to have an algorithm to detect jumps in differenced receiver data, and more generally in any time-series data. USNO is developing such an algorithm.

The algorithm begins by computing a linear fit of two sets of median-filtered data, with the second set directly following the first. Each set is of the same adjustable length. The median filtering helps avoid erroneous fits due to extreme outliers; it outputs the median point at every time epoch. The RMS of each set of data from its respective linear fit is computed as well. Then, the value of each linear fit at the identical point at the end of one fit and beginning of the second fit is computed. If this value differs by more than the greater of the RMS values multiplied by a confidence factor, then a jump is found.

However, a consequence of this method of detection is that points surrounding the actual jump will also be marked – incorrectly – as jump points. Thus, the next step is to examine the set of jump points obtained and add those points that represent good data back into the good datasets. This is done by going over each dataset, from either the first or last estimated jump point towards the end or beginning of the fit, and adding points back into either dataset that are within the $\text{RMS} \times \text{confidence factor}$. Then, the time of the jump is determined to be the midpoint of the remaining excluded jump points. The fits are then re-computed from the new datasets, and the difference of each of these re-computed fits from their offset at the point of the jump is the final value of the jump. Figure 5 shows the result of a run of the filter on a set of data that has a jump and the dataset obtained after correcting the jump according to the result of the final determined value of the jump.

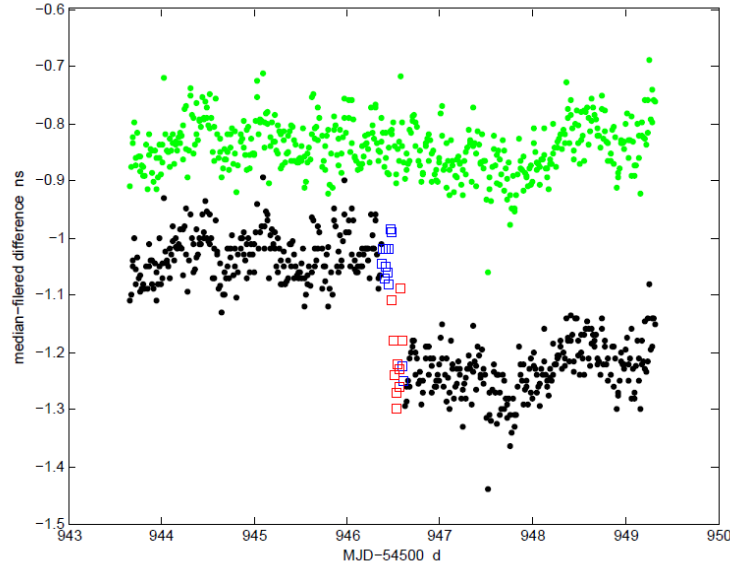


Figure 5. Results of a Run of a Jump Correction Algorithm. The green curve has been offset for emphasis and shows the curve after removing the jump determined by the algorithm. The blue rectangles are points determined by the 2nd dataset fit to be jumps and the red rectangles are jumps as determined by the 1st dataset fit. These points get added back into the datasets since they are not bad points. The confidence factor used here is 3.5.

VII. PPP FOR TIME TRANSFER AND THE EVALUATION OF RECEIVER TIMING INSTABILITY

In recent years the Precise Point Positioning (PPP) algorithm has emerged as a capable method for determining the precise position of a GNSS antenna. It is comparable to results obtained with RTK and online double-differencing tools such as the Online Positioning User Service (OPUS) by the National Geodetic Survey (NGS). The PPP algorithm also generates GNSS receiver differences from the IGS Timescale. Differencing two sets of these differences cancels out IGS Time and allows for a direct comparison of receiver reference clocks.

There are several immediately apparent benefits of using PPP instead of TWSTT for operational time transfer between timing laboratories. Perhaps foremost is the much reduced cost of PPP, which also allows for the presence of a redundant system. An operational TWSTT link is expensive to maintain; while some labs maintain operational TWSTT systems, all labs use some method of GNSS as either a primary or secondary means of time transfer for the generation of TAI. The PPP method requires investment in a modern dual-frequency GPS receiver capable of producing code and carrier phase measurements as well as a dual-frequency GPS antenna. These components are relatively inexpensive compared to the cost of a satellite dish and renting time on a geostationary communications satellite. Other benefits include easier installation and maintenance and well-established methods of data collection and processing.

The BIPM routinely assigns a higher associated uncertainty with PPP time transfer. This is because it lumps modern and older designs together and is forced to generalize from older calibrations that may have spanned system changes at laboratory sites. However, as discussed below, the traveling GPS calibrations that USNO has performed using PPP do not always agree with simultaneous TWSTT calibrations. This will be discussed more later in the paper. Considering the excellent results published by Feldman et al. (PTTI-10) [2], we conclude that more work is necessary to understand the peculiarities of GPS PPP time transfer.

There are several different types of PPP packages and methods of running PPP on data. USNO uses the Natural Resources Canada (NRCAN) PPP package. The NRCAN package has many different methods of processing receiver data to produce a PPP reduction. One day or multiple days of data can be processed at

once. The Kalman Filter is run in the forward and optionally in the backward direction. The backward filter run uses the final parameters of the forward run as the starting parameters. This is contrary to the Kalman Filter optimization mathematics, which take into account parameter aging by appropriate weighting of the independent forward and backward solutions; however, the effect is minimal in the application in which only the middle day out of a 7-day forward/backward run is retained.

The a-priori satellite orbit and clock corrections that are used are user-defined. Options include the IGS Final and Rapid orbits and clocks, as well as those generated by the individual laboratories contributing to the IGS. Experimental support is provided as well by NRCan for using combined GPS+GLONASS products to compute GLONASS and combined GPS/GLONASS PPP.

USNO operationally uses the backward filter run of either a single day of data or of the 4th day (the middle day) of a 7-day PPP run, chosen to minimize day boundary jumps per Guyennon et al. [3]. Both rapid and final IGS products are used. Reductions are computed daily.

Using PPP on GNSS receivers operating on a common antenna and clock, it is possible to discern individual receiver characteristics as well as obtain an estimate of the noise of the PPP method. In Figure 6, the receiver differences are plotted against USN3. Each of the curves features highly correlated behavior, suggesting that there is instability originating from USN3. USN3 was the primary USNO SPS receiver until September 2012. Plots such as this one were used as evidence supporting a change of the primary receiver.

The plot in Figure 7 shows the same data, but using USN6 as the common differenced receiver instead of USN3. The instability of USN3 is apparent in this figure. Note the interesting daily sawtooth behavior in the curve of USN6-USN4. This sawtooth behavior appears to be rooted in USN4 and lacks any current explanation. Suspected items are code-carrier smoothing, which is present by default in NovAtel receivers, and multipath mitigation technologies. Code/carrier divergence (when there is a long-term slope between code and carrier phase measurements) could be relevant, and in follow-up studies we will compare data extracted directly from the Rinex files. The curve for USN6-USN5 is very flat. These are both NovAtel receivers, albeit of different generations. Still, similarities in hardware could account for such similar behavior.

Figure 8 shows the Time Deviation of the data shown in Figure 7. At short averaging times, the USN6-USN5 data are slightly less stable, but as τ increases they quickly come to be the most stable and by a generous margin. The daily sawtooth behavior noted in the USN4 curves is also apparent in the differences, contributing to worse stability with $\tau \cong 0.5$ days. With longer averaging, however, the sawtooth is effectively compensated and the stability is markedly better than USN6-USN3. There is also a valley at 1 day of averaging, which is likely due to the canceling of daily systematics associated with GPS tracking (multipath, satellite orbits, etc.). The differences featuring only 21st century receivers fall below 10 picoseconds at $\tau = 1$ day. This suggests that the PPP method has a very favorable noise floor at $\tau \geq 1$ day for modern systems, at least for receivers sharing a common antenna.

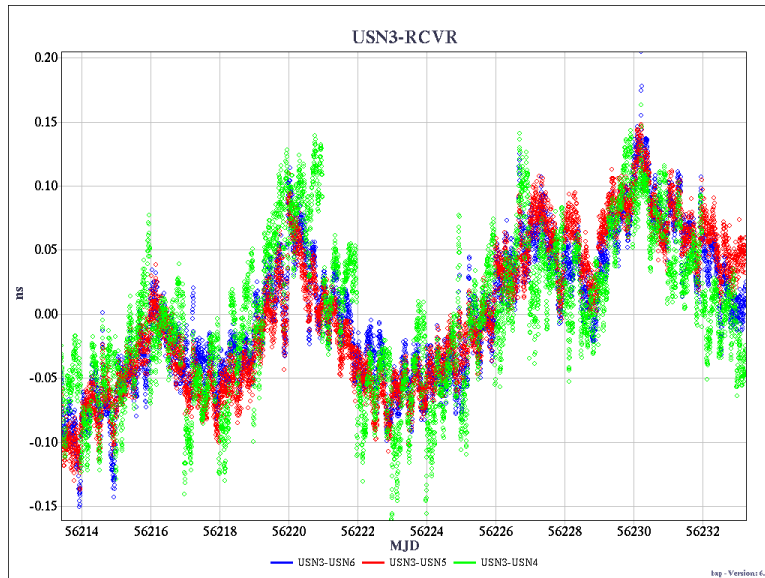


Figure 6. USN3 minus other GNSS Receivers. This plot shows the PPP reductions of several different GNSS receivers operating in a common clock and antenna configuration. The curves were computed by differencing the Rapid IGS orbits and the 4th day of 7-day PPP runs from the individual receivers. Note the highly correlated behavior of the curves, suggesting instability in the USN3 receiver.

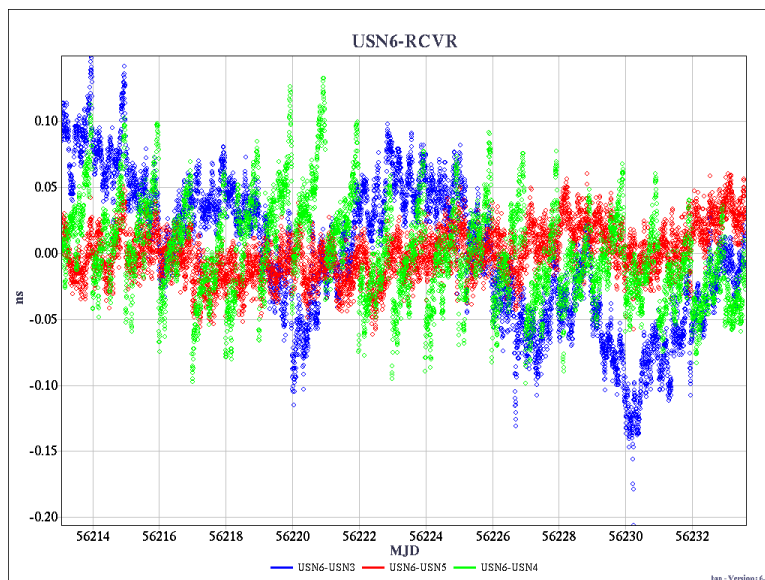


Figure 7. USN6 minus other GNSS Receivers. This plot shows the same data as in the previous plot, but using USN6 as the common receiver in the differences. Additional behavior is more pronounced when using a more stable receiver as the common receiver.

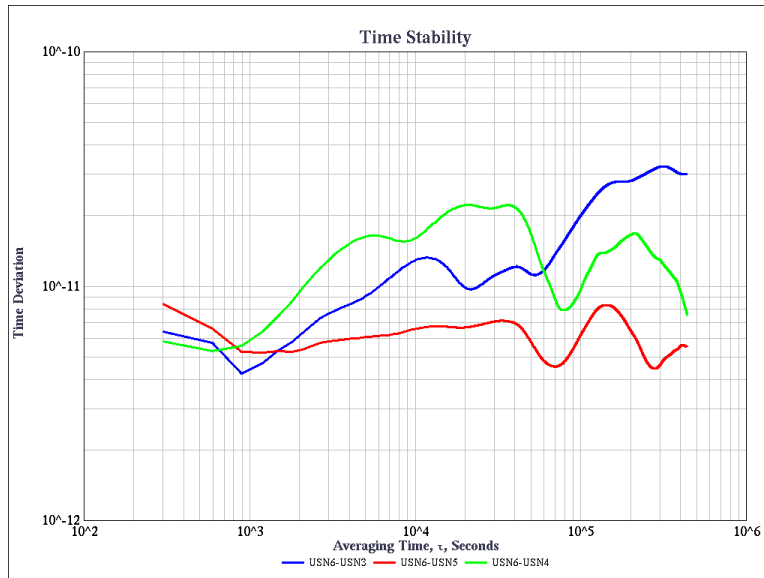


Figure 8. Time Stability of GNSS Receiver Differences. USN6-USN5 is slightly worse at minimal τ , but quickly becomes by a good margin the most stable difference. USN6-USN4 stability is hampered up to 1-day by the sawtooth behavior. There is a valley at 1-day averaging times likely due to daily systematics canceling.

VIII. REMOTE CALIBRATION WITH GPS

USNO's interest in GPS Time Transfer follows the above discussion on using PPP for Time Transfer. GPS calibration trips would be more cost effective than TWSTT calibration trips. Instead of having to either drive a huge vehicle cross-country or ship several large palettes of TWSTT gear and rent satellite time to do the communications, USNO personnel could conduct the trips using a GPS receiver and associated equipment that can easily fit in carry-on luggage. When calibrating timing laboratories with the proper staff, it would not even be necessary to send USNO personnel. They could assemble the system and run the data collection themselves. We would run the data processing and analysis after the system is returned.

For the past couple years, we have been sending a GPS time transfer setup with selected TWSTT calibration trips in an experimental capacity. These trips are still very much a work in progress; the results do not always agree with the parallel TWSTT results.

The source of this disparity has been elusive. In theory, a GPS time transfer setup should be relatively simple. It requires only the delay from the on-time point of the reference clock of the 1 pulse per second (PPS) signal and the tick-to-phase delay from the 1 PPS to the rising edge of the frequency reference. From there, all that is left to do is determine the system calibration at USNO and then transfer that calibration to the traveling setup at the remote location to determine the site calibration. Figure 9 shows that closure agreement between GPS time transfer trips is within a couple nanoseconds. Each of the data gaps represents a time when the system was out for a calibration trip. The difference between any set of gaps is at most around 1.5 ns. Although this is higher than expected, it cannot explain our calibration discrepancies, which can differ by as much as 30 ns from TWSTT.

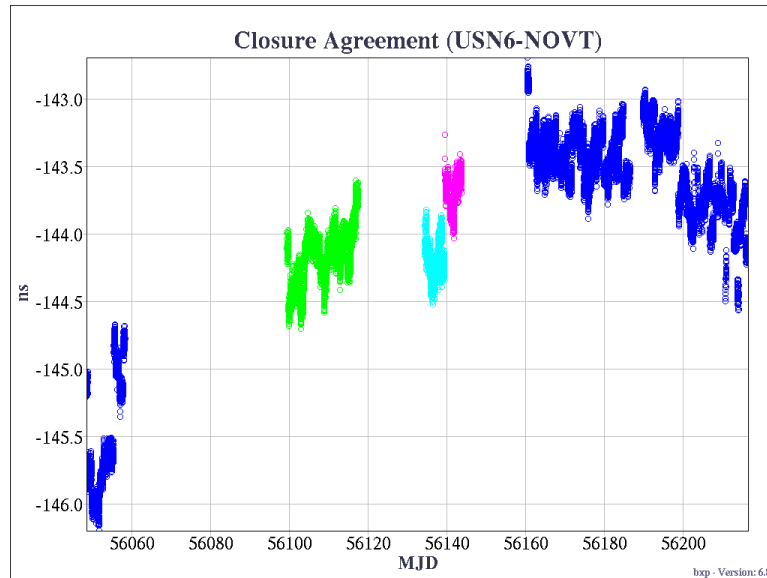


Figure 9. Closure agreement of USNO GPS Time Transfer Trips. The data gaps occur when the system is out on a calibration trip.

Possible error sources such as miscalibration of the port-to-port delays on the signal amplifiers, and temperature sensitivities should be relatively small (i.e. less than a few ns). It may be that the receiver or some traveling component of the system loses calibration in shipment. In all calibrations to-date no correction has been applied for the difference between the incoming PPS/10Mhz and the PPS created by the receiver from those inputs – this is the tick-to-tick measurement [4]. To the extent that it is constant, this correction would be irrelevant; however, it will be measured and applied in future calibrations. On the other hand, the 50 ns ambiguity due to the 20 MHz internal reference cannot be the problem since the discrepancies are not multiples of 50 ns. It should be noted that for the MINOS experiment, NIST used NovAtel receivers as their traveling receivers and computed their calibrations using the tick-to-tick instead of the tick-to-phase, and these calibrations agreed with the portable TWSTT calibrations within 1 ns [4].

Figure 10 shows a recent calibration trip to NIST. The TWSTT calibration differed from the GPS calibration by about 7 ns. See Zhang et al. [5] for more information on the calibration of USNO and NIST. Figure 11 shows the difference between receivers USN6 and NIST during the same timeframe. There is a jump at MJD 56121.9 that is common across all of the PPP datasets. Looking at other receivers (USN3, AMC2) against NIST shows that it is the NIST receiver that underwent a small jump. It is interesting to note the behavior of the PPP solutions after the jump. The day boundary jump after the 56121.9 jump in the single day solutions resulted in those solutions returning to normal much sooner than the multiday solutions, which required about 4 days; this is consistent with our understanding of the software. The delay accumulation in the USN6-NIST data is the same as in the traveling receiver data.

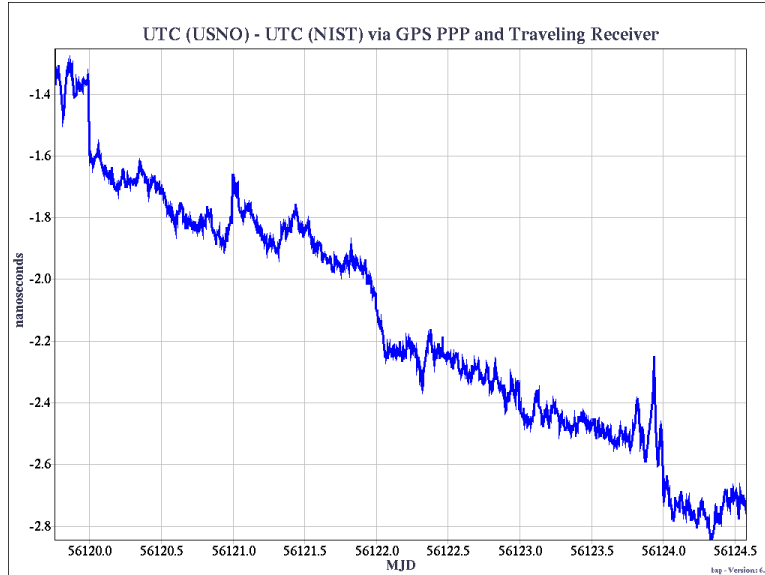


Figure 10. A recent GPS calibration trip to NIST. The associated TWSTT calibration for this trip differed by 7 ns.

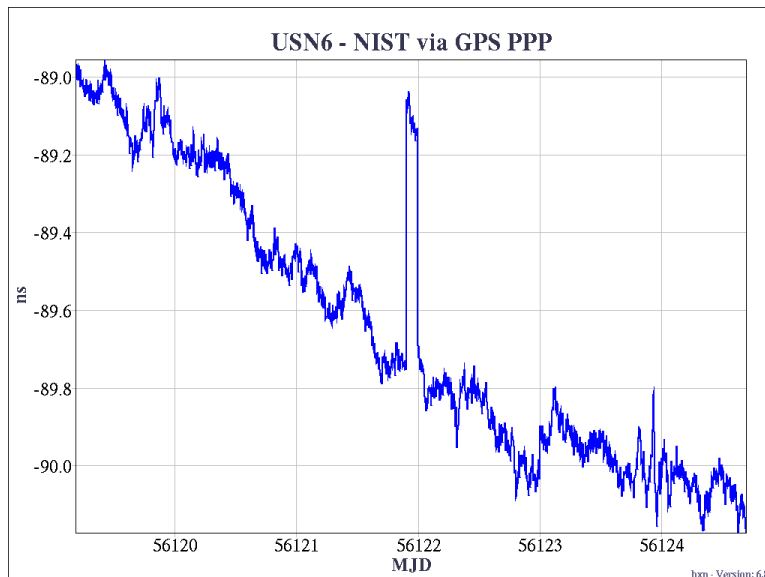


Figure 11. NOV1-NIST via GPS PPP. The jump seen at MJD 56121.9 in NIST is present in all of the different types of PPP processing and with different reference receivers. The time wander seen in Figure 10 is also in Figure 11.

IX. IGS MGEX

The IGS Multi-GNSS Experiment (MGEX) is a pilot program to facilitate the collection and archiving of modern GNSS receivers in the multi-GNSS, multi-signal capable file format of RINEX 3. The MGEX represents the future of data exchange among timing laboratories. In addition to readying the data archive servers of the IGS for the new data types, the tools, such as the Hatanaka compression tools `rxn2crx` and `crx2rxn`, must be updated. The data flow and processing at the contributing laboratories have to be modified to handle RINEX 3. In short, the MGEX provides contributing laboratories and data archive servers the opportunity to modify their procedures to handle what will be the future method of GNSS data transfer.

USNO contributes receiver data from two multi-GNSS receivers to the IGS MGEX in compact RINEX (Hatanaka compressed) format which is then further compressed using gzip. The receivers contributed are listed below:

- USN4: This receiver is also known internally as SPX3. It is a Septentrio PolaRx4TR Pro. It is one of only two Septentrio receivers in the MGEX.
- USN5: This receiver is also known internally as NOV2. It is a NovAtel FlexPak6 (based on the OEM628 board). It is the only NovAtel receiver in the MGEX, although other receivers may be based on a NovAtel board.

X. GPS-TO-GNSS TIME OFFSET (GGTO)

GPS Time currently is a composite of many ground clocks and the many GPS satellite clocks. Each GPS satellite broadcasts as part of its navigation message the offset of its clock from GPS Time. Using this precise timing information as well as the broadcast position, the user is able to obtain precise timing and positioning in real time.

Other GNSS systems work in a similar fashion. But, the timescales of other GNSS are not synchronized to GPS. Thus, when attempting to use multiple satellites from multiple systems, this additional timing offset must be a part of the solution. In ordinary circumstances this is not an issue.

It is beneficial to the user to use many satellites to increase the geometry of and to reduce the noise of the solution. With a clear view of the sky and a good receiver, it is not an issue to track a number of satellites of each system and add an additional satellite to the solution to solve for the timing offset between GNSS systems. There is no further work required by system operators to aid users in this situation. However, in challenging environments such as urban canyons and with foliage cover, it is difficult enough to obtain a solution at all. It is advantageous to be able to use every satellite in view to calculate a position, and there may only be a satellite or two in view from each system. This scenario is where it is important to have the GGTO information on hand; it avoids having to lose a satellite in the solution in order to calculate the GGTO value. In support of this, GPS will in the future broadcast a GGTO value, calculated at USNO, for several systems.

USNO is aiding the U. S. Air Force and coordinating with other systems operators in working to provide this information operationally at a future time. Currently, we are collecting data for GLONASS and GALILEO. We also have software tools in place which can generate GGTO calculations. However, there are issues before these tools can be run in an operational setup.

With both systems there is the issue of receiver calibration. There are currently no calibrated Galileo or GLONASS receivers at USNO. To properly compute the GGTO, one has to know the receiver timing delay associated with each signal of interest. This is especially challenging with GLONASS satellites since there is a different delay for each broadcast frequency. It will be necessary to calibrate a test receiver on a simulator to be able to determine all of these delays. Then, using this test receiver in a common antenna and clock with the operation receiver(s) of interest, it will be possible to transfer this calibration via comparison of raw signal measurements.

With GALILEO, there is an additional issue of data availability. Many of the in-orbit GALILEO satellites do not broadcast a usable navigation message. It is desirable from the standpoint of remaining independent to limit outside connections. Thus, we wish to obtain navigation information for the system in question directly from the satellites and to apply post-processing corrections, if available, only after an initial solution is obtained. However, as the system is in its infancy, this issue will be corrected as the system approaches operational capability.

Once solutions are available to these outstanding issues, USNO should be able to implement quickly and in an operational capacity the transfer of GGTO values.

XI. CONCLUSIONS

USNO is the PTTI manager for the U. S. DoD. We actively research and develop technologies and products in areas from astrometry and clocks to local and wide area time transfer. In this paper, a few of the projects of the Time Service department with applications to GNSS positioning and time transfer have been outlined.

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